The Problem of PHOSPHATE FERTILIZERS

Their relation to the phosphate-supplying power of the soil and to the requirements of farm crops

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BULLETIN 484
UNIVERSITY OF ILLINOIS
AGRICULTURAL EXPERIMENT STATION

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This material was first presented as an address before the annual meeting of the Illinois Agricultural Association at St. Louis, Missouri, in January, 1941.

ACKNOWLEDGMENT

For much of the research in soils and plant nutrition which has been utilized in developing the point of view explained in this publication, the author is indebted to R. H. Bray, Associate Chief in Soil Survey Analysis, I. R. Hoener, First Assistant in Soil Fertility, and E. B. Earley, formerly Assistant in Soil Fertility.

Urbana, Illinois April, 1942

Publications in the Bulletin series report the results of investigations made or sponsored by the Experiment Station

The Problem of Phosphate Fertilizers

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IT IS WELL KNOWN that farm crops, as well as other plants, require phosphorus for their normal growth, and also that this phosphorus is obtained from the soil chiefly, if not entirely, in the form of the simple phosphate ion. Whether or not a given soil requires phosphate fertilizers in order to produce adequate crops depends, of course, upon its own phosphate-supplying power in relation to the needs of those crops.

The phosphate-supplying power of any given soil is not determined primarily by its total phosphorus content, for much of the phosphates are in forms only very slowly available to plants. Comparatively poor soils contain in the upper 15 to 18 inches, the depth to which the feeding roots penetrate in large numbers, enough phosphorus to provide for maximum crops for upward of a century if all the phosphorus were accessible to the growing plants; crops at more probable yields would be supplied for two or three centuries.

PHOSPHORUS-SUPPLYING POWER OF SOILS

From the standpoint of actual performance in crop production, the phosphorus-supplying power of a soil must be evaluated by its ability to deliver phosphorus to the growing crops in usable form and at such rates that there will be no shortages in the tissues of the plants at any stage of their growth. After all, the one purpose in the management of soils is to so feed the crops that grow in them that an abundant harvest may be realized; and there is no point to accumulating great reserves of phosphorus (or any other plant-food substance) in the soil unless these reserves adequately feed this year's crop and the next and the next. If the reserves fail to do this and maximum yields are to be obtained, the soil supply must be supplemented by applications of phosphate in suitable forms and in sufficient quantities to make up the deficiency.

The process of soil development not only consists of the disintegration of rock or mineral parent substances and the redistribution within the soil of the products formed, but it also involves the accumulation of partially decayed products of vegetation from which the content of organic matter is gradually built up. This organic matter accumulates in the upper layers of the soil.

In the process of plant growth the inorganic, or mineral, forms of phosphorus taken up by the plant are changed into organic forms and in these changed forms they are returned to the soil when the plants decay in place or are plowed under, so that what was originally mineral phosphorus eventually becomes an actual part of the soil organic matter. This process had gone so far during the long period of soil formation preceding the breaking of our soils with the plow, that today in Illinois, even in the light-colored soils that are poor in organic matter, 30 percent or more of the total phosphorus in the plowed depth is present in the organic forms. In the dark-colored corn-belt soils these organic forms constitute 40 to 60 percent of the total phosphorus.

Fresh organic materials, such as straw, plant roots, cornstalks, and green plants, contain besides organic phosphorus considerable amounts of water-soluble inorganic phosphate. When these materials are returned to the soil, this inorganic phosphate becomes instantly available to absorbing roots that make contact with it. It remains soluble and fully available in the plant residues until they are almost disintegrated. Then the phosphorus gradually escapes into the soil mass and becomes a part of the soil.

Forms of Soil Phosphorus

At least three different forms of soil phosphorus are thus seen to be related to the phosphorus-supplying power of the soil; and a fourth is also known to be important.

Soluble phosphate. One form of phosphate already mentioned is the instantly available soluble form temporarily retained in fresh and actively decaying plant residues. The amount of this form of phosphorus in a soil varies greatly according to the way in which the soil is managed and the crop rotations that are chosen; and even in the same soil the amount differs greatly from year to year. There is very little other water-soluble phosphate in field soils.

Organic phosphorus. The second form of phosphorus which contributes to the phosphorus-supplying power of the soil is that contained in the more permanent stock of soil organic matter. It is released for crop use as inorganic phosphate by the decay of the organic matter thru bacterial action. This reserve of organic phosphorus which gradually releases soluble phosphate is an important cause of the well-known high fertility of corn-belt soils. Fifty to seventy-five years of exhaustive cropping, however, have caused significant decreases in the organic-matter content of these soils, including the content of organic phosphorus, with the result that their productive capacity has been markedly impaired.

Phosphatic minerals. A third source of phosphorus for growing plants is the phosphatic minerals in the soil, both primary and secondary. These minerals were the only forms of phosphorus in the original soil-forming, or parent, material. In humid regions the minerals now present in the soil, mainly of the secondary kind, have withstood rainfall, weathering, and leaching for many centuries and will probably continue to do so. Having such resistant powers, they naturally are not a source from which phosphate ions can readily dissolve so as to be taken into plant roots. But the delivery of phosphate from these mineral particles into the roots is not dependent entirely on their dissolving in the soil water. The moist root hairs, which make up the feeding surfaces of the roots, "freeze" themselves tightly to the mineral surfaces. The thin film of moisture that then exists between the root hair and the mineral particle is separated somewhat from the free soil solution. This moisture film, concentrated against the mineral surface and reinforced by the root-hair excretions, chiefly carbonic acid, has a solvent power that is greater at this contact point than in the free soil solution. The most direct avenue of escape for the dissolved phosphate then is the root hair.

Different species of plants vary in their ability to obtain phosphates from comparatively insoluble minerals by the method just described. Of the cultivated crop plants, some of the legumes, such as red clover, alfalfa, and sweet clover, are particularly efficient. Those in the grass family, such as wheat, oats, corn, and pasture grasses, are intermediate. Others, such as many of the vegetable crops, are still lower in efficiency.

Adsorbed phosphate. There is still a fourth form of phosphorus for growing plants which has been found to exist in soils. This form is known as adsorbed phosphorus[6, 18*] and is in equilibrium with the soil water. It is in the nature of phosphate ions held on the surface of colloidal clay particles somewhat as replaceable potassium and calcium are held. Because soluble phosphate, from organic or other sources, is picked up and held by the soil clay as adsorbed phosphate or else is

*These and similar numbers thruout the text refer to literature citations on pages 581 and 582.

taken up by growing plants, very little phosphorus is lost from the soil by leaching. Altho the adsorbed phosphate has a high degree of availability at the point of root contact, its degree of availability is limited by the fact that it is not appreciably mobile in the soil. There are also indications that its ease of recovery in soluble form, and possibly its availability to plants, decreases with aging.[21*] However, studies made to date indicate that if the amount of adsorbed phosphate is sufficiently large it can satisfy all the phosphorus requirements of growing crops.[6*]

Phosphate Deficiencies in Illinois Soils

The power of the soil to supply phosphorus for growing crops is determined by the combined amounts of this element available from the four sources just described and perhaps from other forms as well.

When long-continued cropping has impaired soil productivity and this has been accompanied, as is usually the case, by the removal of the more readily available forms of phosphorus in harvested crops, the available supply of phosphorus in the soil becomes inadequate for the further production of large yields of crops. That such phosphorus deficiency does exist is shown by crop responses to added phosphates, and the degree of the deficiency is indicated by the size of the increases that are obtained in carefully controlled field experiments. When phosphate deficiencies occur, it is time to find the remedy and the best one, if possible.

Results obtained on Illinois experiment fields and confirmed by observations on farms have indicated that in the northern two-thirds of the state there are two large zones of difference in soils. In the eastern one-third to one-half of this area the soils are more responsive to phosphate fertilizers than the soils farther to the west (Fig. 1).

All the reasons for this difference are not yet fully known, tho one reason doubtlessly goes back to the differences in the origin of these soils. In the area toward the west the soils were developed from loessal, or wind-laid, parent material; whereas toward the east glacial till was an important soil-forming material, the layer of loess covering the till being very thin. These loessal soils of northern and central Illinois contain more of the readily available forms of phosphorus than the till-derived soils; hence phosphorus is less frequently the limiting element in the production of high crop yields. In this part of the state variations in response to phosphate fertilizers are directly correlated with the degree of phosphorus deficiency.

In the southern third of Illinois an entirely different situation exists. Phosphate deficiency is widespread and severe, but phosphate fertilization does not so generally solve the problem of poor crop yields. Poor drainage, soil acidity, shortage of nitrogen and potassium, or poor seasonal distribution of the water supply limit growth and yield just as seriously as does the deficiency of phosphorus. Wherever these other limiting factors are absent or are corrected, increases in yield follow the application of phosphates. An example is furnished by the experiments on the Elizabethtown field in Hardin county.

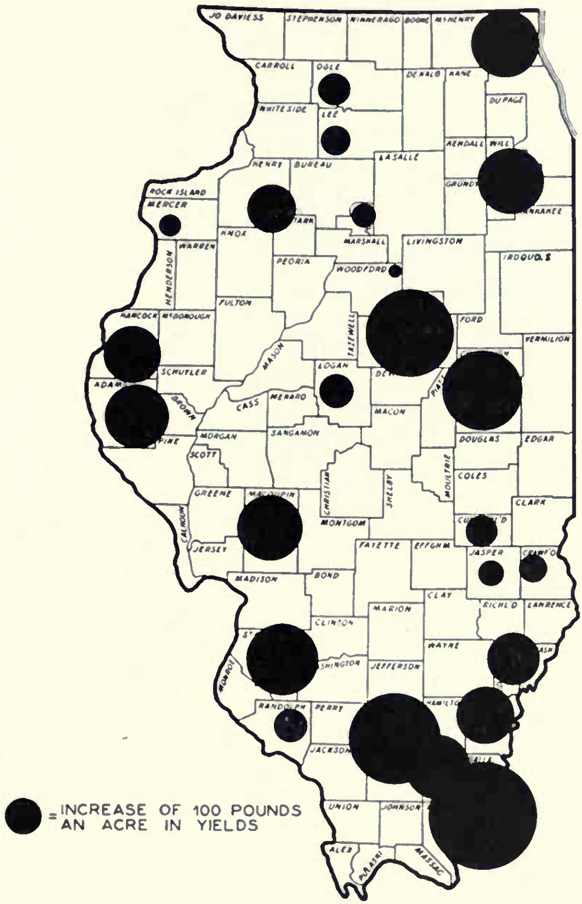

Fig. 1.—Regional response to phosphate fertilizers as measured by increase in crop yields on Illinois experiment fields

The increases are for both the hay and the grain of the corn, oat, and wheat crops as an average for four years. Rock phosphate was used on all 24 fields except at Antioch in Lake county and Bloomington in McLean county, where bonemeal was used instead.

In addition to regional variations in the phosphate-supplying power of soils, many local differences occur. It is because of these local variations that chemical soil tests, or so-called "quick tests," have been used extensively to indicate what farms, fields, or parts of fields are in need of phosphate fertilizers.

CROP REQUIREMENTS FOR PHOSPHORUS

Obviously a major consideration in determining the best means of restoring the phosphorus-supplying power of the soil is the requirements of the various crops for phosphorus. Crop requirements moreover are to be considered not only as the total amount of phosphorus removed from the soil per acre by a mature crop—a point of view long held—but they are to be considered also as the concentration of this material needed in the tissues of the plant at various stages of development in order to promote maximum growth and yield.

The first critical stage in phosphate nutrition is the early life of the plant. If it is stunted then by a phosphorus shortage in the tissues, there will be difficulty in overcoming the handicap in later months, even with a good supply of phosphorus, because at the later stage the plant will have lost to some extent its capacity for growth.

Another critical stage in the life of a plant, in relation to the phosphate supply, occurs at the onset of reproduction, or seed formation, when phosphorus is needed in the young seeds. With the corn plant this is at the tasseling and shooting stage. If the stalk cannot furnish the phosphorus needed at this critical time, seed development will suffer unless the shortage can be made up from the soil. If the stalk supply is seriously deficient, the shortage cannot be made up at this late date and grain production will be reduced even tho there may be an abundant supply of available phosphorus in the soil.

Legumes and Their Ability to Make Phosphorus Available

As previously stated, different species of plants differ greatly in their ability to take phosphorus from the soil, especially from the relatively insoluble phosphatic minerals. One group of plants that has great ability in this respect includes some of the most important legumes.

Three legume crops are of particular interest because of their superior ability for taking phosphorus from slowly soluble mineral forms, such as rock phosphate, and the even less soluble phosphatic minerals native to the soil. These are red clover, sweet clover, and alfalfa. They require large amounts of phosphorus and, when grown under favorable conditions without a phosphate handicap, they contain more phosphorus per ton of dry crop than most nonlegumes.

This ability of legumes to utilize rock phosphate has been clearly illustrated by experiments. Sweet clover grown in sand culture in the

Fig. 2.—Coating of rock phosphate was taken from plaster-of-paris slabs by sweet-clover roots

Transplanted into a sand culture beside these slabs, these clover plants dissolved most of the phosphate coating in a few weeks, as shown by the white areas. Their closely matted roots completely covered the surface of the slabs.

greenhouse was so effective in dissolving rock phosphate that its roots etched nearly white a slab of plaster of paris that had been coated with rock phosphate (Fig. 2).

In another experiment sweet clover made even better growth with rock phosphate than with superphosphate when these forms were added to different jars of phosphorus-deficient soil (Fig. 3). This feat of rapidly utilizing phosphate directly from rock phosphate cannot be accomplished by wheat or corn even when rock phosphate is present in excessive amounts, and this helps to explain the value of sweet clover as a soil-improving crop when plowed back into the soil.

The same experiment with sweet clover demonstrated that the

Fig. 3.—Spring wheat and sweet clover planted immediately after the addition of phosphate to phosphorus-deficient soil

Rock phosphate of different degrees of fineness was applied to the five center jars. Sweet clover made immediate use of this phosphate, as shown by the growth in these jars compared with that in the two end jars. Even the 60-to-100 mesh particles were effective. The spring wheat profited much more from the superphosphate (jar at extreme right). The poor clover growth in this jar may be partly due to competition with the vigorously growing wheat.

plants had a marked ability to obtain phosphorus from relatively coarse phosphate particles (Fig. 3). This ability, not shown by corn or wheat grown in jars with similar soil, indicates that when rock phosphate is used with sweet clover and other legumes, a satisfactory degree of fineness is obtained when 90 percent will pass thru a 200-mesh sieve and all the fines produced in the grinding are included. The validity of this conclusion is also borne out by trials carried out on the Illinois experiment fields.[3*]

In addition to its ability to convert relatively insoluble phosphatic minerals into forms more readily available to other crops, sweet clover, like other deep-rooting plants, tends to bring phosphorus up from the deeper soil layers and deposit it on or near the surface of the soil if the above-ground parts of the plants are not harvested. Even if the crop is harvested, some of this deep supply of phosphorus is returned to the surface soil with the upper roots and stubble; thus phosphorus is added to the upper soil layers at the expense of the deeper layers.

The upward movement of soil phosphorus caused by a deep-rooting crop may be illustrated by observations on field soils. On one of the

Morrow plots at Urbana, where corn was grown continuously for more than sixty years and only the stubble and roots were returned, soil samples taken in 1904 showed a high test for acid-soluble phosphorus thruout the upper 20 inches. Nine years later (1913) the surface soil (0 to 7 inches) still gave a high test, but from that depth down to 20 inches this form of phosphorus had been exhausted and a low test was obtained. These results indicate that the acid-soluble phosphorus was depleted more rapidly from the subsurface than from the surface soil, which was enriched with the phosphorus contained in the upper roots and stubble. After ten more years (1923), as well as after twenty more years (1933), even the surface soil was exhausted of its acid-soluble phosphorus and a low test was obtained in the entire 20 inches.

Another instance which shows that soil phosphorus has been transferred upward is the greater concentration of total phosphorus found near the surface of virgin grassland soils as compared with the strata immediately underlying them. During the several thousand years that the prairie soils were developing, the roots of the grasses removed a portion of the phosphorus from all the depths to which they penetrated. Year after year the top growth with its accumulated phosphorus was returned to the surface of the soil.

Where the top growth of deep-rooting legumes is plowed down for green manure, the upward transfer of phosphorus is facilitated by the superior ability of these species to tap the resistant mineral phosphates, as well as by their deep-rooting habits. Thus the surface soil is enriched at the expense of the deeper soil layers, and at the same time the organic forms are increased at the expense of the mineral forms.

Sweet clover, in common with other deep-rooting legumes, possesses this ability to make available the phosphorus of phosphatic minerals and to transfer it from the subsurface to the upper soil layers. As a result, this crop is of great practical value in improving the phosphate fertility of field soils when used in a limestone-sweet-clover program. On many of the Illinois experiment fields which chemical tests and crop yields had shown were phosphorus-deficient, a limestone-sweet-clover program changed the soil after some years to a medium- or high-testing soil and also increased crop yields to such a degree that phosphate applications gave little or no further response. On other soils the same limestone-sweet-clover program failed to produce similar improvement. Obviously variations occur in the forms of soil phosphorus in different soils, and these variations affect the phosphorus-supplying power of the soil and the soil's response to the limestone-sweet-clover method of management. Chemical methods are now being devised to distinguish these different forms of soil phosphorus and to determine their amounts.

Phosphate Nutrition of Corn

Early stage of growth. For one to two weeks after germination a young corn seedling is abundantly supplied with phosphorus from the reserves present in the seed. Then this supply suddenly stops and the young plant is dependent upon its own very small root system for obtaining from the soil the phosphate that it needs. This is the first critical stage in the growth of the corn plant in relation to the phosphate supply. Plants at this early stage can contact but a fraction of one percent of the soil volume that they will be able to tap later when they have developed a large and greatly branched root system. In order, therefore, to maintain the necessary phosphorus concentration in its tissues (from .3 to .35 percent) there must be an adequate supply of easily soluble phosphate within reach of the few roots the young plant possesses. Otherwise it will stop growing and, after some time, its leaves will become reddish purple and many of them will die at the tips (page 557).

All these symptoms of phosphorus deficiency have been observed during the last several years in many cornfields, in June and early July especially. Invariably they have been associated with phosphorus starvation *in the tissues,* as shown by chemical analyses made in 1940 of purple stunted field-grown plants and normal green ones at many locations in Illinois (Table 1). At each location except at Hartsburg and Bloomington the corresponding normal green and purple stunted plants of any pair grew in nearby hills or rows in the same field or experimental plot. In no case did the phosphorus content of purple plants reach a percentage as high as the lowest percentage among the green plants (Table 1). In studies continued from 1938 thru 1941 the soils in which purple and stunted young corn plants grew were found usually but not always to test low in phosphorus.

In some of the fields examined, phosphorus-starved corn plants grew on high-testing soil, but these plants were infested at their roots with insects, commonly with the grape colaspis, which in the larval form feeds upon root hairs and fine fibrous roots, thereby partly depriving the plant of its only means of absorbing nutrients.

In other fields where purple-leaved young plants were growing in soils testing high in phosphorus, the high test was due to the presence

TABLE 1.—PHOSPHORUS CONTENT OF STUNTED YOUNG CORN PLANTS WITH PURPLE LEAVES AND NORMAL PLANTS WITH GREEN LEAVES

Field	Soil	Treatment[a]	Phosphorus content	
			Purple plants	Green plants
			perct.	*perct.*
Newton	Cisne silt loam	RLrPK	.160	.274
		RLrPK	.182	.365
		RLrPK	.178	.298
		RLrP	.258	.368
Rantoul	Muscatine silt loam	None	.180	.384
Hartsburg	Grundy clay loam	Varied	.153[b]	.277[c]
			....	.349[d]
Bloomington	Dark-colored silt loam	None	.173	....
Average		.....	.183	.331

[a]Treatment is represented by the following symbols: R = crop residues, including legumes as green manure when legumes will grow; L = limestone; rP = rock phosphate; K = muriate of potash. [b]No soil treatment. [c]Residues, limestone, legumes. [d]Residues and superphosphate.

of mineral phosphates that were only slowly available to the plants but which were still soluble in the acid used for soil testing.[a] These minerals, which may include native soil minerals or rock phosphate, or both, do not furnish phosphate ions to the young corn plants rapidly enough to meet their requirements at this stage of growth; and where the deficiency symptoms occurred, this phosphorus supply was not supplemented by large enough amounts of the more rapidly available forms. Investigations now in progress strongly indicate that soils such as that just described—high-testing soils growing purple and stunted corn plants that do not show root injury—are usually deficient in the adsorbed form of phosphate even tho the content of acid-soluble phosphate, as shown by the Illinois soil test, may be relatively high.

In cornfields that are phosphorus-deficient the purple plants usually recover their green color later in the season and grow to maturity, but they yield notably less than plants in fields where the early stunting did not occur.

This same failure to recover completely from earlier phosphate starvation was observed in controlled sand cultures. The phosphate was withheld for the first two to three weeks, so that growth ceased and the young plants became stunted and purple. Then soluble phosphate was supplied in abundance and the plants quickly acquired a green color, as well as normal phosphorus concentration, and resumed

[a]The Illinois phosphorus test solution is here referred to. It has a hydrochloric-acid concentration of .7 normal.[5*]

growth. They did not, however, completely recover from the earlier starvation. They grew more slowly at first and tasseled and matured later. Other corn plants grown in sand cultures and supplied with abundant rock phosphate in the optimum acidity range around pH 6.3 were found to contain after the seedling stage not more than .17 percent of phosphorus. This is approximately half the percentage found in normal plants grown without a phosphorus handicap. This same result has been obtained where the corn was grown in 100 percent rock phosphate and fed a nutrient solution minus phosphate but otherwise complete and balanced.[9*]

These studies show a definite limitation of the rate at which corn plants can obtain phosphorus directly from rock phosphate; and they indicate that if corn growing in the field contains the normal percentage of phosphorus (.3 to .35 percent), it is taking a portion of it from forms more rapidly available than rock phosphate.

Tasseling and shooting stage. The second critical stage of growth in the corn plant with regard to its phosphorus requirement is at tasseling and shooting time. Here begins a whole new cycle of life similar to the seedling stage in that a new plant is being grown from the fertilized ovule even tho this tiny plant will remain dormant in the matured seed until germination. A high concentration of phosphorus is therefore again required in the tissues of the young shoot, particularly in the ovule. Analyses show that these beginning seeds contain from .5 to .7 percent of phosphorus—twice as much as the normal concentration in the actively growing vegetative plants earlier in the season.

At tasseling and shooting time the stalks and leaves furnish the principal supply of phosphorus to the shoots, and it is necessary that the plants be well nourished up to this time. Previously it was noted that very young corn plants growing in a rock-phosphate concentration as high as 100 percent did not acquire a higher concentration of phosphorus than .17 percent, or half the normal amount, altho the plants themselves appeared as large and vigorous as those which, grown with soluble phosphate, contained the usual .33 percent of phosphorus. However, the plants supplied with rock phosphate began to lose their leaves when the shoots appeared. First the lower leaves became yellow and died and then others in succession, until in 10 to 12 days after shooting, the leaves were all dead; no ears were produced. The plants that had been continuously supplied with soluble phosphate contained more than .3 percent phosphorus up until shooting time and remained green during the development and ripening of the grain.

Even when the corn plant receives an abundant supply of phosphorus during the vegetative period, it later requires an additional intake thru the roots because the reserve in the stalks and leaves is apparently not large enough to carry the plant from tasseling to maturity. This fact was shown by corn grown in sand culture with adequate soluble phosphate which was later taken away (Fig. 4). When the phosphate was withdrawn after the first 5 weeks, the plants grew to normal size and tasseled but no shoots were formed. When the plants were allowed to grow 7 weeks before the phosphate supply was stopped, both tassels and shoots appeared but the ears were very

Fig. 4.—Corn plants deprived of phosphorus before maturity

These corn plants were given abundant phosphate in soluble form during the early stages of growth. Deprived of phosphorus after 5 weeks, the plants at the left grew to normal size but failed to produce shoots. Altho the plants at the right received phosphorus during the first 7 weeks, they produced only small nubbins (the reduced vegetative growth was caused by early transplanting). All plants were given an adequate and continuous supply of all nutrient salts other than phosphorus. Compare these deficient plants with the normal ones shown on the following page.

small nubbins. Adjacent plants continuously fed soluble phosphate matured normal ears (Fig. 5).

Fig. 5.—Corn plants given a continuous and adequate supply of soluble phosphate

These corn plants, which received adequate amounts of phosphorus and other nutrient salts thruout their life span, produced normal ears. Compare with the deficient plants shown in Fig. 4. Both groups of plants were grown outdoors in quartz sand. They were planted on June 5 and photographed on September 27, 1934.

Phosphate fertilizers for corn. These studies of corn nutrition afford some suggestions as to the use of phosphate fertilizers for this crop. Corn fits conveniently into a rotation following a small grain seeded with sweet clover as a companion crop. The sweet clover is plowed down early the next spring to be used as green manure for the corn. This arrangement makes it possible to feed the corn with

Phosphorus hunger causes purpling of leaves in most strains of corn

(Reproduced from *Hunger Signs in Crops* thru courtesy of American Society of Agronomy and National Fertilizer Association) part or all of its phosphate thru the agency of sweet clover from rock phosphate applied either ahead of the small grain and clover or with it. For moderate to high yields of corn, rock phosphate thus used with sweet clover has often supplied all the phosphorus needed and there are numerous field experiments in Illinois in which no further increase was obtained when superphosphate was added.

Where conditions aside from phosphate permit very high yields, the additional phosphate required for the higher yields may not be obtained rapidly enough from the soil and from the rock phosphate applied with the preceding sweet clover crop. In such cases a more quickly available source, such as superphosphate is necessary, especially in the early stage of growth when the root system is small. Use of superphosphate or other soluble phosphate has thus become of increasing importance where high-yielding hybrids are grown.

With high-yielding hybrids, however, another limiting factor must usually be considered in connection with phosphorus. Since corn has a high potassium requirement, amounts sufficient for ordinary yields become inadequate for very high yields. It is for this reason that mixed fertilizers containing both phosphate and potash have been effective in growing high yields of corn on productive soils where superphosphate without potash failed to produce maximum yields.

With the thicker stand necessary for exceptionally high yields and with each plant bearing an ear, phosphate must be supplied rapidly enough so that, even with the increased competition, the plants can obtain the amount of phosphorus required for unrestricted growth, particularly at the two critical periods discussed previously. In other words, very high production requires a more mobile supply of fertilizer elements than production on a somewhat lower plane.

Wheat Growth and the Phosphate Supply

Phosphate nutrition. The physiology of wheat nutrition in its general aspects is similar to that of corn. The same critical stages as to phosphate requirement occur and need to be dealt with in similar fashion. There is this difference, however: winter wheat, like the legumes, has a longer life span than corn. About 270 days are required from planting to harvest; whereas corn must mature its grain in a little more than half that time. The longer life span may account in part for the ability of winter wheat to make better use of rock phosphate than corn can make. Spring wheat, however, which has a shorter life span than corn, also has responded directly to rock-phosphate applications in soil cultures in the greenhouse (Figs. 3 and 6). Therefore

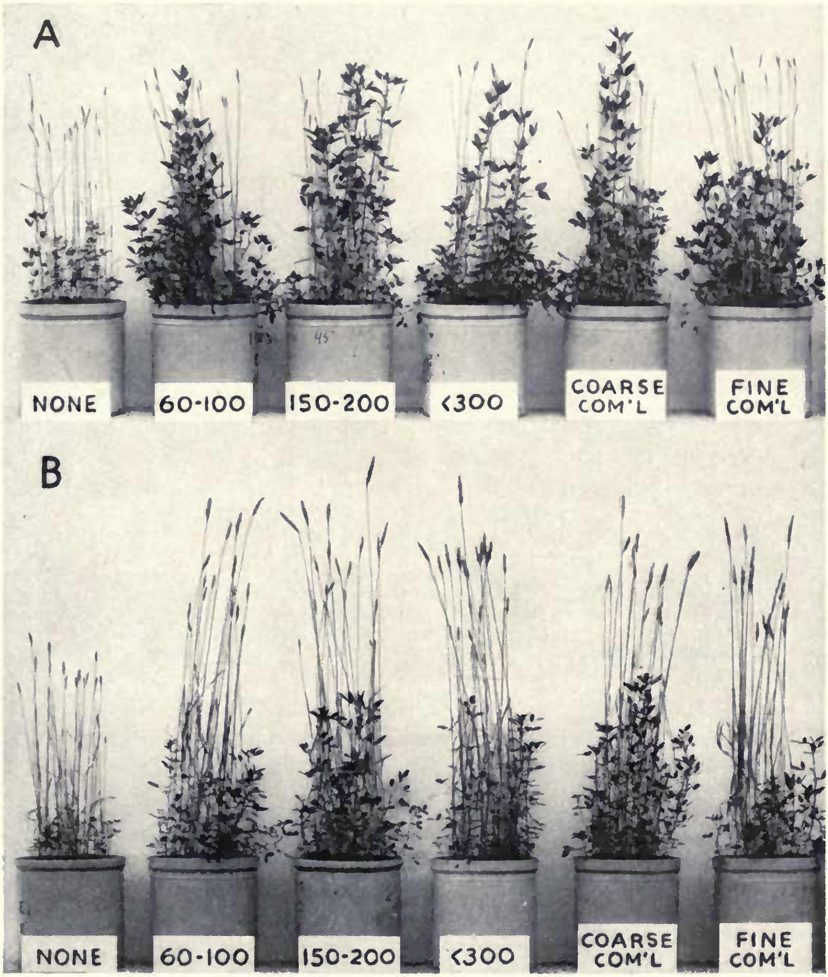

Fig. 6.—Sweet clover makes rock phosphate available to succeeding crops

Note contrast in wheat growth in two series of jars, all of which (except the extreme left jar in each series) received rock phosphate of different degrees of fineness. In top row (**A**) a rotation of corn, buckwheat, and then corn, and in the lower row (**B**) a rotation of spring wheat, sweet clover, and then corn preceded the present crop and followed the application of rock phosphate. The effect of the sweet clover residues in making the rock phosphate available for the wheat even tho a corn crop intervened is clearly shown in **B**. Field experiments confirmed these results.

TABLE 2.—ANNUAL ACRE-YIELDS OF WHEAT GROWN WITH AND WITHOUT NITROGEN AND PHOSPHATE FERTILIZERS[a]
(Minonk field, 1912–1940)

Year	Grain yields on Plot 407 (RL long-time treatment)		Grain yields on Plot 408 (RLrP long-time treatment)	
	Whole plot			
	bu.		bu.	
1912	39		41	
1917	21		23	
1921	26		29	
1924	38		41	
	South half	North half[b]	South half	North half[b]
	bu.	bu.	bu.	bu.
1928	20	22	24	24
1932	31	36	30	37
1936	36	39	40	41
1940	15	38(sP)	19	32(sP)[c]
M7[d]	30	32	33	34
M3[e]	29	32	31	34

[a]The author is indebted to F. C. Bauer for the hitherto unpublished data on yields in 1936 and 1940. [b]Except in 1940, wheat on the north half of the plot was top-dressed with nitrogen at the rate of 33 pounds an acre in the form of either nitrate of soda or sulfate of ammonia. No nitrogen was used for the 1940 crop, but superphosphate was drilled with the seed. [c]See footnote, page 571. [d]M7 is the mean yield of the 7 crops preceding 1940 (last 30 years). [e]M3 is the mean yield of the 3 crops preceding 1940 (last 12 years).

the difference in the length of the life span hardly gives a complete explanation of wheat's greater utilization of phosphorus from rock phosphate. Nevertheless, wheat is well known to be less efficient than

TABLE 3.—WEIGHT AND PHOSPHORUS CONTENT OF ABOVE-GROUND PORTIONS OF WHEAT PLANTS GROWN WITH AND WITHOUT SUPERPHOSPHATE
(Minonk field)

Additional treatment for 1940 wheat	Plot 407 (RL), 100 plants			Plot 408 (RLrP), 100 plants		
	Dry weight	Phosphorus content		Dry weight	Phosphorus content	
Samples taken May 6, 1940						
	grams	perct.	mg.	grams	perct.	mg.
None (S½)	7	.181	13	7	.187	13
Superphosphate (N½)	20	.387	77	16	.373	60
Samples taken May 31, 1941						
None (S½)	44	.275	121	43	.255	110
Superphosphate (N½)	128	.212	271	127	.204	259

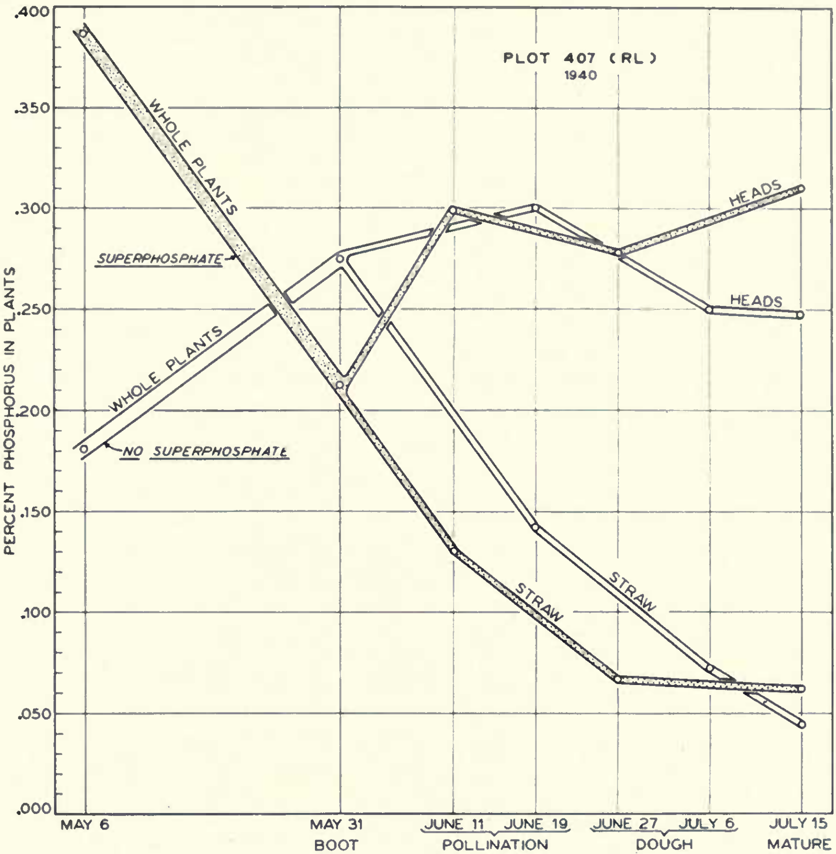

Fig. 7.—Phosphorus concentration in wheat plants at successive stages when grown with and without superphosphate on soil treated with residues and limestone

When no superphosphate was used, the phosphorus concentration in the plants in their early growth (May 6) was half the normal amount. Drilling superphosphate with the seed prevented this deficiency and doubled the yield (Table 2), altho the percentage of phosphorus in the plants at the later stages was essentially the same with both treatments.

sweet clover, alfalfa, and other legumes in utilizing the phosphorus of rock phosphate, and for this reason the wheat crop profits, as does corn, when sweet clover is used as an intermediary crop to convert the phosphorus of rock phosphate into more readily usable forms (Fig. 6).

An opportunity to study in some detail the critical stages in the growth of the wheat plant at different levels of phosphorus feeding was afforded by the wheat crop grown on the Minonk experiment field in 1940.

Plot 408 had received a basic treatment of crop residues, limestone, and rock phosphate since 1910. During this same time sweet clover had been grown and plowed down as a green manure. The present crop rotation, in use on this plot since 1923, is: (1) corn,

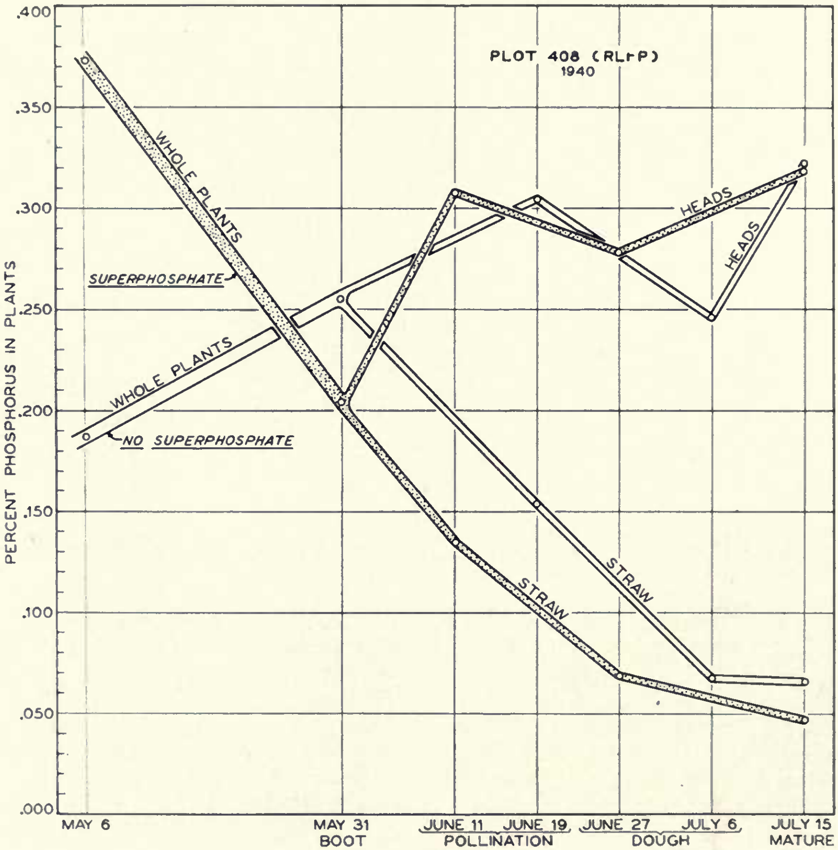

Fig. 8.—Phosphorus concentration in wheat plants at successive stages when grown with and without superphosphate on soil treated with residues, limestone, and rock phosphate

Even the long-time use of rock phosphate did not provide adequate available phosphate to the plants at the early critical stage (May 6). Consequently drilling superphosphate with the seed produced results similar to those on the plot that was not treated with rock phosphate (Fig. 7).

(2) corn, (3) oats with sweet clover, and (4) wheat with sweet clover. Plot 407 was handled similarly except that no rock phosphate was applied. The average wheat yield on Plot 408, where rock phosphate was used, was 33 bushels an acre for the seven crops grown during the whole period preceding 1940 (1910-1939); on Plot 407, where the wheat was grown without rock phosphate, the average yield was 30 bushels an acre during the same years (Table 2). The average yield of the three crops grown during the last twelve years of the period (1928-1939) was 31 bushels an acre on the plot with rock phosphate and 29 bushels on the plot without rock phosphate.

In the fall of 1939 superphosphate was drilled with the wheat on the north half of each of these plots by means of a fertilizer attachment. Beginning May 6, 1940, several representative samples of the green wheat plants were obtained at intervals of 12 to 25 days up to the time of maturity. At the early stage of growth reached on May 6, a low percentage concentration of phosphorus (.18 percent) was noted in the plants grown without superphosphate both on Plots 407 and 408 (Figs. 7 and 8 and Table 3). That these plants were not obtaining sufficient phosphorus was indicated by the much more rapid growth during the next 25 days on the superphosphated halves of the plots than on the halves grown without superphosphate (Figs. 9, 10, and 11).

As a result of these differences in growth the weights of the plants

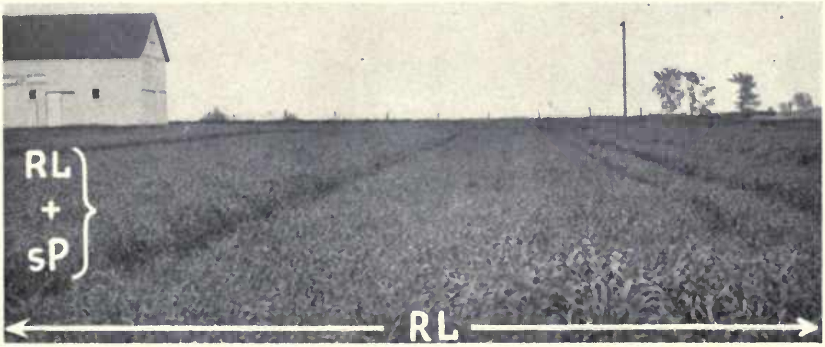

Fig. 9.—Young wheat plants respond to quickly available supply of phosphate

The much more rapid growth made by the wheat plants on the left half of this plot, which received superphosphate in addition to a basic treatment of limestone and legume residues, shows that the young plants need a quickly available supply of phosphorus. The superphosphate was drilled with the wheat when it was seeded in the fall. (*Minonk field, May 31, 1940*)

Fig. 10.—Rock phosphate alone does not supply phosphorus rapidly enough for the wheat crop

Even when basic treatment included rock phosphate in addition to limestone and legume residues, the wheat plants grown with superphosphate on the half plot at the left developed much faster than the adjacent plants which received no superphosphate. (*Minonk field, May 31, 1940*)

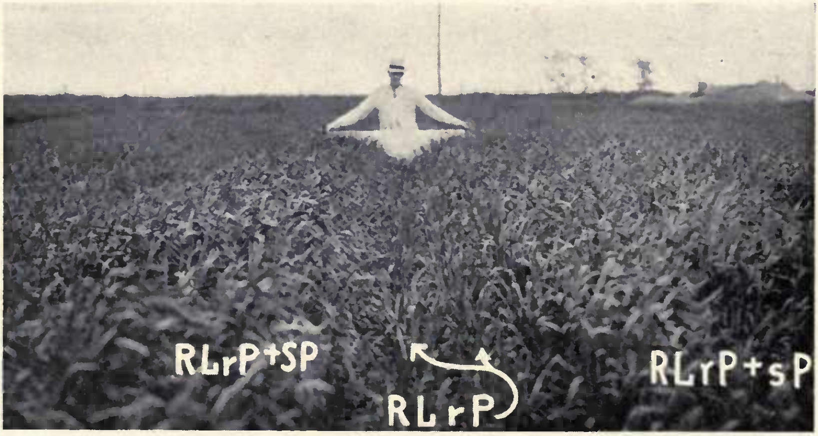

Fig. 11.—Wheat plants dwarfed by inability to reach available phosphorus when young

The wheat plants in the two center rows, which received rock phosphate but no superphosphate, were not able to effectively tap the superphosphate in the adjacent rows, which were only 8 inches distant. As a result the plants did not get enough phosphate at the early stage of growth, a critical time in respect to phosphorus requirements.

on the two halves of the respective plots differed greatly when the next samples were taken on May 31. In fact in the plants receiving superphosphate the additional stimulation of growth was so great that the phosphorus was diluted and its concentration forced below that in the plants not treated with superphosphate. At the same time the plants on the superphosphated plots took up more than twice as much

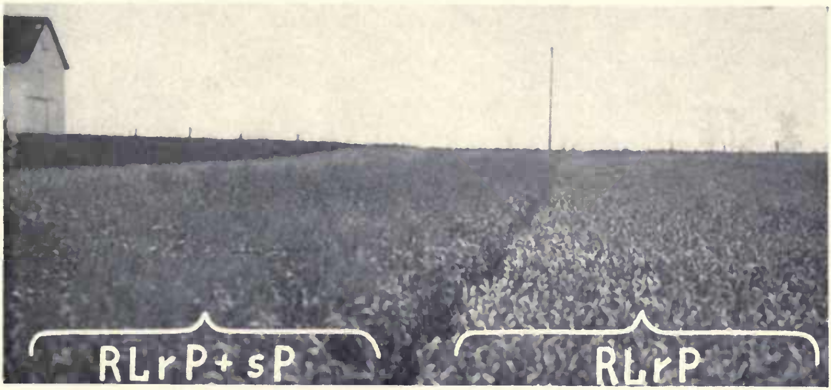

Fig. 12.—Superphosphate hastens ripening of wheat

The wheat on the superphosphated half-plot to the left was fully headed out and in bloom when the picture was taken on June 11, 1940, whereas no heads were visible on the half-plot to the right, which received no superphosphate and did not reach the bloom stage until June 19.

phosphorus as the plants on the plots not receiving this treatment (Table 3). That the early period of growth is a critical time in the life of the wheat plant with regard to its need for phosphorus is shown by the marked differences in growth that were brought about in these tests by the use of superphosphate. The increase in grain yields on the areas where superphosphate was used, as will be shown later, further emphasizes the importance of having an adequate supply of phosphorus available to wheat plants at this critical period.

The second critical stage in the growth of the wheat plant, so far as its need for phosphorus is concerned, is at the onset of reproduction, when the plants are in bloom, and shortly thereafter. At this time phosphorus moves rapidly from the stalks and leaves into the young ovules or seeds. When the plants were in bloom—those on the superphosphated plots on June 11 (Fig. 12) and those grown without superphosphate on June 19—the entire heads of the plants were found

TABLE 4.—PHOSPHORUS IN VEGETATIVE PARTS AND IN HEADS OF WHEAT AT THREE STAGES WHEN GROWN WITH AND WITHOUT SUPERPHOSPHATE
(Minonk field, 1940)

Stage and date of sample	Additional treatment for 1940 wheat	Plot 407 (RL): phosphorus content of—		Plot 408 (RLrP): phosphorus content of—	
		Stalks and leaves	Heads	Stalks and leaves	Heads
		perct.	*perct.*	*perct.*	*perct.*
Pollination					
June 19....	None (S½)...............	.142	.300	.154	.304
June 11....	Superphosphate (N½).....	.130	.299	.135	.307
Dough					
July 6....	None (S½)...............	.073	.239	.068	.227
June 27....	Superphosphate (N½).....	.067	.278	.068	.278
Mature					
July 15....	None (S½)...............	.044	.247[a]	.056	.321[a]
July 15....	Superphosphate (N½).....	.062	.310[a]	.047	.318[a]

[a]At the mature stage the weights and analytical results are given for threshed grain instead of whole heads.

to contain .3 percent phosphorus even tho they had emerged and expanded to full size in the course of only a very few days.[a] In England Knowles and Watkin[16, 17*] observed concentrations of phosphorus up to .41 percent in wheat heads at the same stage. It is practically certain in both the Illinois and the English experiments that the phosphorus concentration in the young ovules would have been found to be much higher had it been feasible to separate them from the whole heads for analysis at this stage of growth. That the movement of phosphorus into the young seeds occurred at the continual expense of the stalks and leaves was shown by a decrease of phosphorus in stalks and leaves to around .14 percent at the bloom stage and to .07 percent at the dough stage (Table 4). The decline continued to about .05 percent at maturity.

The rapid movement of phosphorus from the vegetative parts into the developing seeds, especially at the critical period between the bloom and dough stages, is speeded up when superphosphate has been applied (Figs. 13 and 14). On the half of Plot 407 where no superphosphate was used, 195 milligrams of phosphorus entered the heads during the 17 days from the bloom to the dough stage; on the half where super-

[a]Because plants on the superphosphated half-plots developed more rapidly than those on areas where no superphosphate was applied, samples were taken at intervals about 8 to 9 days apart so as to compare the two groups of plants at the pollination and dough stages. Only one sampling was made at maturity, and that was delayed until the plants grown without superphosphate had ripened.

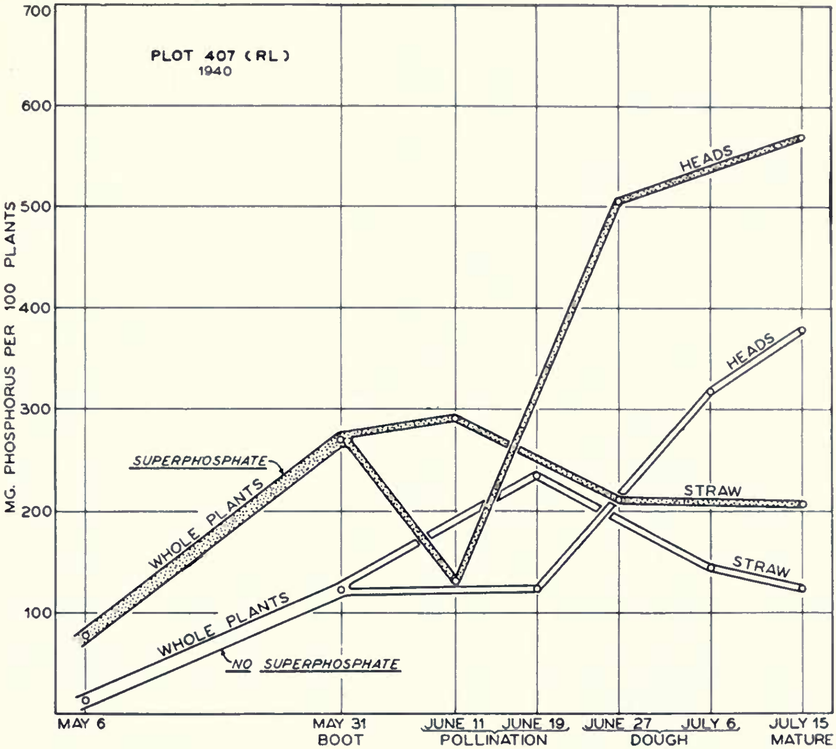

Fig. 13.—Movement of phosphorus into the filling grain of wheat plants grown with and without superphosphate on soil treated with residues and limestone

Superphosphate drilled with the seed caused a greatly accelerated movement of phosphorus into the wheat heads between the pollination and dough stages. This was possible because the superphosphated plants absorbed a large amount of phosphorus during their early growth. On May 6 the superphosphated plants contained almost six times as much phosphate as the plants not receiving superphosphate; by May 31 the amount was a little more than two times as much.

phosphate was applied 374 milligrams, or nearly twice as much phosphorus, was transferred in the same length of time, as can be calculated from the data given in Table 5. The accelerating effect of superphosphate is even more strikingly shown on Plot 408, where its application resulted in the transfer of 2.65 times as much phosphorus from stalk and leaves into the heads as occurred when it was not used.

TABLE 5.—WEIGHT AND PHOSPHORUS CONTENT OF VEGETATIVE PARTS AND HEADS OF WHEAT PLANTS AT THREE STAGES WHEN GROWN WITH AND WITHOUT SUPERPHOSPHATE
(Minonk field, 1940)

Stage and date of sample	Additional treatment for 1940 wheat	Plot 407 (RL) 100 plants		Plot 408 (RLrP) 100 plants	
		Stalks and leaves	Heads	Stalks and leaves	Heads
		Dry weight			
		grams	*grams*	*grams*	*grams*
Pollination					
June 19....	None (S½)...............	166	41	230	57
June 11....	Superphosphate (N½).....	223	44	259	54
Dough					
July 6....	None (S½)...............	200	127	212	134
June 27....	Superphosphate (N½).....	313	182	340	182
Mature					
July 15....	None (S½)...............	279	153[a]	228	100[a]
July 15....	Superphosphate (N½).....	332	184[a]	359	198[a]
		Total phosphorus content			
		mg.	*mg.*	*mg.*	*mg.*
Pollination					
June 19....	None (S½)...............	236	123	354	173
June 11....	Superphosphate (N½).....	290	132	350	166
Dough					
July 6....	None (S½)...............	146	304	144	304
June 27....	Superphosphate (N½).....	210	506	231	506
Mature					
July 15....	None (S½)...............	123	378[a]	128	321[a]
July 15....	Superphosphate (N½).....	206	570[a]	169	630[a]

[a]At the mature stage the weights and analytical results are given for threshed grain instead of whole heads.

TABLE 6.—AVERAGE DRY WEIGHT OF ABOVE-GROUND PORTIONS OF 100 WHEAT PLANTS AT SUCCESSIVE GROWTH STAGES WHEN GROWN WITH AND WITHOUT SUPERPHOSPHATE
(Minonk field, 1940)

Growth stage	Weight on Plot 407 (RL)		Weight on Plot 408 (RLrP)	
	Without sP[a]	With sP[a]	Without sP[a]	With sP[a]
	grams	*grams*	*grams*	*grams*
May 6...........................	7	20	7	16
May 31..........................	44	128	43	127
Bloom...........................	207	267	287	313
Dough...........................	327	495	346	522
Mature..........................	432	516	328	557

[a]Superphosphate.

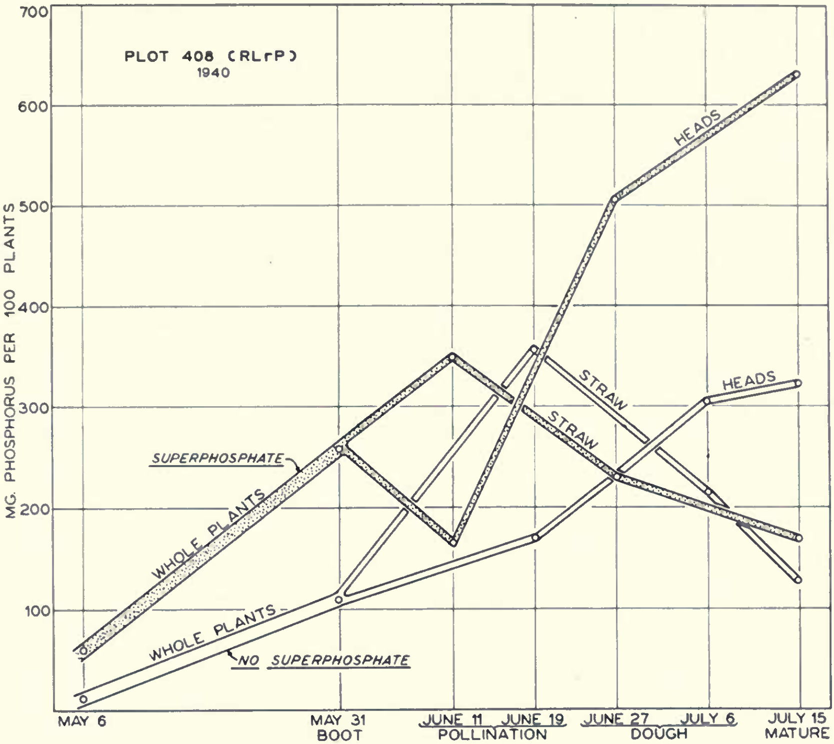

Fig. 14.—Movement of phosphorus into the filling grain of wheat plants grown with and without superphosphate on soil treated with residues, limestone, and rock phosphate

Altho the soil had received a basic treatment of rock phosphate, the addition of superphosphate caused an accelerated movement of phosphorus into the wheat heads between the pollination and dough stages. This rapid transfer was possible because, during the early period of growth, the superphosphated plants had absorbed much more phosphorus than the other plants, just as they did on the soil not treated with rock phosphate (Fig. 13).

It has not yet been determined whether the phosphorus already accumulated in the stalks and leaves at heading time can supply all the needs of the crop during the last few weeks, or whether phosphorus uptake from the soil is necessary. Gericke[13, 14*] in California grew wheat in water culture and supplied it with adequate phosphates until heading, at which time the phosphorus was entirely withdrawn. From the time of heading up to maturity the stalks and leaves furnished sufficient phosphorus for development of the grain.

A gain in total weight of the wheat plants grown on the Minonk

TABLE 7.—AVERAGE GAINS IN DRY WEIGHT OF 100 WHEAT PLANTS DURING SUCCESSIVE GROWTH STAGES
(Minonk field, 1940)

Period	Kind of gain[a]	Gain on Plot 407 (RL)		Gain on Plot 408 (RLrP)	
		Without sP	With sP	Without sP	With sP
		grams	*grams*	*grams*	*grams*
Beginning to May 6	P	7	20	7	16
	D	.....	.....	.....	.....
May 6 to boot (May 31)	P	37	108	36	111
	D	1.5	4.3	1.4	4.4
May 31 to bloom	P	163	139	244	186
	D	8.6	12.6	12.8	16.9
Bloom to dough	P	120	228	59	209
	D	7.1	14.2	3.5	13.1
Dough to maturity	P	105	21	−18	35
	D	11.7	([b])	.....	([b])

[a]P designates gain for period; D, the average daily gain. [b]The time when the superphosphated plants matured was not determined. Only one sampling was made at maturity and that was delayed until the plants grown without superphosphate had ripened.

experiment field indicated that growth continued in most cases to maturity, tho the rate was retarded toward the end (Tables 6 and 7). Likewise, the amount of total phosphorus in the whole plant indicated a slowing down but not a complete cessation of phosphorus absorption from the soil as the plant approached maturity (Table 8 and Fig. 15).

TABLE 8.—AVERAGE PHOSPHORUS UPTAKE FROM THE SOIL BY 100 WHEAT PLANTS DURING SUCCESSIVE GROWTH STAGES
(Minonk field, 1940)

Period	Kind of gain[a]	Phosphorus uptake on Plot 407 (RL)		Phosphorus uptake on Plot 408 (RLrP)	
		Without sP	With sP	Without sP	With sP
		mg.	*mg.*	*mg.*	*mg.*
Beginning to May 6	P	13	77	13	60
	D	.....	.....	.....	.....
May 6 to boot (May 31)	P	108	194	97	199
	D	4.3	7.8	3.9	8.0
May 31 to bloom	P	238	151	417	257
	D	12.5	13.7	22.0	23.4
Bloom to dough	P	91	294	−79	221
	D	5.4	18.4	.....	13.8
Dough to maturity	P	51	60	1.0	62
	D	5.7	([b])	.....	([b])

[a]P designates gain for period; D, the average daily gain. [b]The time when the superphosphated plants matured was not determined. Only one sampling was made at maturity and that was delayed until the plants grown without superphosphate had ripened.

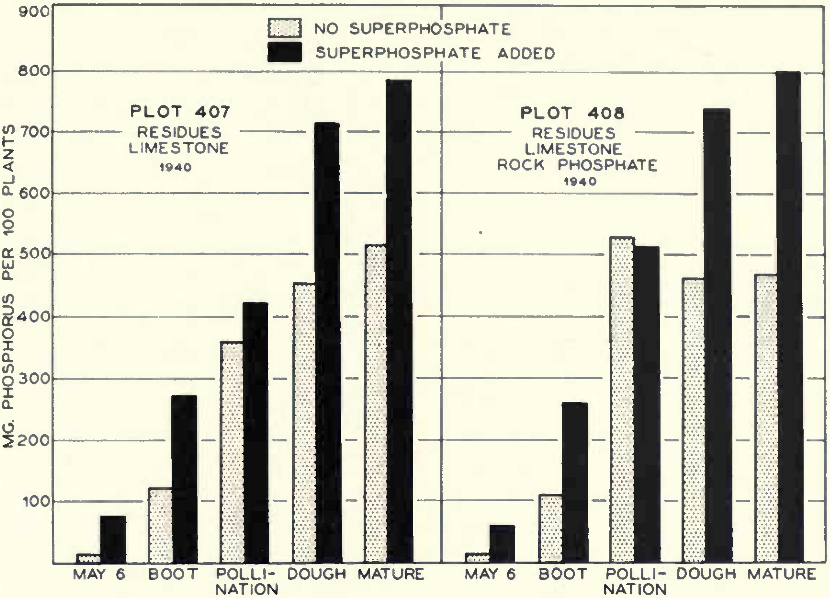

Fig. 15.—Phosphorus content of entire wheat plants at different stages of development when grown under different soil treatments

Except on that part of Plot 408 which received no superphosphate, the plants took up phosphorus steadily until maturity. Where rock phosphate was used alone, the absorption ceased at pollination; by this time these plants had taken up more phosphorus than those on Plot 407 that had simply the soil supply to draw upon. The plants receiving only rock phosphate probably ceased to absorb phosphorus because they had stored enough to fill the needs of their potential grain yield, which was much smaller than that of the superphosphated plants on both plots.

The importance of a sufficiently high concentration of phosphorus in wheat plants during the critical stages of growth is still further reflected in the increased yields obtained in 1940 at the Minonk field when superphosphate was used. Plot 407, with a basic treatment of crop residues and limestone, yielded 15 bushels an acre without superphosphate and 38 bushels where superphosphate had been drilled with the seed. On Plot 408, which had received the additional basic treatment of rock phosphate, the yield was 19 bushels an acre without superphosphate and 32 bushels with superphosphate.[a]

[a]This 32-bushel yield does not indicate the full effect of the superphosphate on this plot because the drill failed to apply it to the whole area. The corrected yield for full application of superphosphate is 41 bushels an acre.

Structural characteristics of plants associated with the phosphorus supply. An attempt was made to determine what characteristics of the structure of wheat plants were primarily responsible for the differences in yield of grain on the different plots. The characters expected to play a part are: (1) number of head-bearing tillers per plant, (2) length of heads, that is, number of spikelets per head, (3) number of seeds per spikelet, and (4) weight per seed. It was assumed that the drilling of the seed and germination were uniform.

Of the four variable factors mentioned, the one which appeared most important—the number of head-bearing tillers per plant—proved difficult if not impossible to determine with accuracy; hence the values given are subject to some error. Before heading, the tillers attached to any plant could readily be distinguished. Toward maturity, however, the tillers that did not bear heads died and disappeared. Also, if some of the head-bearing tillers separated from the main stem without leaving distinct scars, they could easily have been mistaken for individual plants. On Plot 407, with a basic treatment of crop residues and limestone, superphosphate increased the number of head-bearing tillers by 34 percent (Table 9); while on Plot 408, which received rock phosphate as a part of the basic treatment, the increase for superphosphate was 45 percent.

The next most important plant character influencing yield was the number of spikelets per head. The other two characters measured—number of seeds per spikelet and average weight of a seed—were not consistently effective in determining yield increases.

In a previous experiment in which wheat was grown in phosphorus-deficient soil under greenhouse conditions, little tillering occurred; increases in yields resulting from superphosphate treatment lay principally in a larger number of spikelets per head and more seeds per spikelet.

TABLE 9.—STRUCTURAL CHARACTERISTICS AND YIELDS OF WHEAT PLANTS GROWN WITH AND WITHOUT SUPERPHOSPHATE
(Minonk field, 1940)

Additional treatment for 1940 wheat	Number of head-bearing tillers per plant	Number of spikelets per head	Number of seeds per spikelet	Average weight of seed	Yield of grain per 100 plants
Plot 407 (RL)				*mg.*	*grams*
Without superphosphate....	2.31	13.7	1.85	27.3	153
With superphosphate.......	3.09	14.4	1.86	25.4	184
Plot 408 (RLrP)					
Without superphosphate....	2.16	13.1	1.40	35.0	100
With superphosphate.......	3.14	14.4	2.04	24.9	198

Yearly variations in phosphorus-supplying power of the soil. The large increase in yields which occurred on the Minonk field when superphosphate was applied for the 1940 crop, the first year it was used there, was unusual (Table 2). Frequent repetitions of so large an increase are hardly to be expected since previous yields on these plots when no superphosphate was used have usually been higher than they were on the nonsuperphosphated areas in 1940.

During the twelve years preceding the superphosphate experiment of 1940, wheat growing on the north halves of Plots 407 and 408 was given nitrogen either in the form of nitrate of soda or ammonium sulfate. For the 1940 wheat crop the nitrogen fertilizers were omitted and the superphosphate treatments added to these half plots. One might suspect that the increased wheat yields in 1940 were partly caused by a residual effect of the nitrogen. The validity of this suggestion is discounted, however, by two observations. In the first place, experiments at the Rothamsted Experiment Station in England[15*] have demonstrated that nitrogen fertilizers applied to wheat in a given year do not show a residual effect on wheat seeded the following year. On the Minonk field the last nitrogen application had been made four years before. Secondly, nitrogen treatments on these wheat plots produced only small and inconsistent increases in yield, indicating that the wheat crop was not being appreciably restricted by a shortage of soil nitrogen (Table 2).

Further problems to solve. In view of (1) the widely fluctuating yields of wheat on Plots 407 and 408 in different years, (2) the small and variable responses to nitrogen fertilizer in different seasons, and (3) the pronounced response to superphosphate in 1940, it is evident that the phosphorus-supplying power of the soil on the Minonk field has varied greatly from year to year. A major object of this investigation, which is still in progress, is to determine the conditions which cause these variations, so they can be eliminated and the supply of phosphorus brought to a sufficiently high level every year. This study of wheat nutrition will therefore be continued thru a number of seasons and will be accompanied by corresponding measurements of seasonal changes in the amounts of the different forms of phosphorus present in the soil.

Raising productivity to very high levels may be expected to bring new problems. Using superphosphate to secure large yields of wheat when this crop is seeded with sweet clover is a case in point. The heavy wheat growth often results in failure of the sweet clover, which in turn may cause lower corn yields the following year. The problem of maintaining sweet clover when wheat yields are very high has not yet been solved, altho drilling the wheat in widely spaced rows has been tried with partial success. Problems such as this may well be looked upon as a challenge to further effort rather than as signals to abandon the ground that has been gained.

RELATION OF LIMING TO PHOSPHATE EFFECTIVENESS

The question of the effect of liming on phosphate effectiveness needs to be considered in its relation to the native soil phosphorus compounds and also to phosphate fertilizers.

Liming and Soil Phosphorus

Liming the soil favorably influences the ultimate utilization of both the mineral and the organic forms of soil phosphorus by growing crops. Just how the lime acts upon the phosphorus has not as yet been accurately described, but it does not necessarily have a direct effect upon availability. It is known that with the organic forms, which, as previously mentioned, make up a significant part of the total phosphorus in the surface soil, liming affects the bacteria producing decomposition. By increasing the numbers of these bacteria and speeding up their activity, liming accelerates the release of soluble, inorganic phosphate, which is readily available to growing plants.[7, 10, 24, 26*] It is true, of course, that some of the organic phosphorus is recombined into organic form in the bodies of the bacteria, but this is easily broken down upon their death.

What happens to inorganic or mineral phosphates when soil is limed is not so well known. Limestone is nearly always applied as a part of soil-improvement plans which include also the growing of clovers or other legumes for green manure. Thus the results observed are really brought about by a combination of limestone and legumes. Such a lime-legume system begun on acid soil will cause increases in the size of crops removed and in the amount of phosphorus obtained from the soil by these crops, as is well known from experiments[1-3, 30, 31*] and from observations on farms. It is certain that a part—perhaps a large part—of the increased phosphorus thus made available and removed by crops has been obtained by clovers from the mineral forms in the soil and subsequently released for other crops when the clover residues decompose; and it is highly probable that a portion of the phosphorus is released more directly as a result of chemical reactions brought about by the use of lime or limestone.

That phosphorus is released as a result of a chemical reaction caused by lime has been suggested by many experimental observations. For instance, Parker and Tidmore[23*] found in laboratory experiments in Alabama that the addition of lime to soils of that state increased the concentration of phosphate in the soil water. Later Scarseth[27*] and Scarseth and Tidmore[29*] found that phosphate was removed from solution and held by the colloidal clay in the soil, the "tightness" of fixation increasing with larger proportions of iron in the clay and decreasing with decreasing acidity.[28*]

Finally, soil acidity has been found to be associated with phosphorus deficiency. Investigations at the Illinois Station have shown that the most mature soils in the state are the most highly acid and are among the soils most deficient in available forms of phosphorus. Coupled with these findings is the observation of Kurtz[18*] that while phosphate recently adsorbed by soil clays can be almost completely removed by successive water extractions, the difficulty of extraction increases with the aging of the clay-phosphate combination. Such experimental findings support the observation previously mentioned—that liming acid soils results in increased removal of phosphorus by subsequent crops grown in good rotations.

Thus while the exact nature of the action of lime upon soil phosphorus is not fully understood, these observations strengthen the view that liming acid soil exerts beneficial effects on the native soil phosphorus both by making possible its appropriation by legumes and by increasing its availability thru alteration of its chemical status in the soil.[a]

Phosphate Fertilizers and Liming

When limestone is added to the soil, from two to four years are required before all of it is converted from calcium carbonate into calcium clay as a part of the soil itself.[8*] During this period any free calcium carbonate present will keep the soil in an alkaline condition in the areas immediately surrounding the calcium carbonate particles.[b] If the alkaline areas predominate, the free calcium carbonate may thus retard the intake of phosphorus from rock phosphate by those crops which are not particularly "strong feeders" on this form of phosphate

[a]Further discussion of this question will be found in the literature citations Nos. 4, 11, 12, 19, 20, 21, 22.

[b]Free calcium carbonate in the form of coarse limestone particles about ⅕ inch and larger is disregarded in this discussion because such particles remain in the soil for ten to fifteen years or more, dissolving too slowly to exert more than a very slight effect on soil conditions or phosphate behavior.[23*]

Fig. 16.—Liming affects availability of phosphate for wheat

Note the poorer growth of wheat in jars of Series **B** compared with Series **A**. Both series (except for the jars at the extreme left and right) received rock phosphate, in the amounts indicated on the jars, at the time the wheat was seeded; but **B** was treated with limestone at seeding time at the rate of 1,000 pounds per acre. While the limestone markedly decreased the availability of the rock phosphate, it had only a slight effect on the availability of the superphosphate (jar at extreme right).

(Fig. 16). These crops, as previously mentioned, include corn, the small grains, and other plants in the grass family.

Because an alkaline condition in the soil interferes with the availability of rock phosphate, the question has often been raised: should rock phosphate be used only in an acid type of agriculture, or on soils which are so slightly acid as not to need liming? That is, should rock phosphate and limestone be kept apart in the soil management system? The answer is found in the soil reactions and in the way in which rock phosphate is fitted into the rotation, as already discussed.

In the first place the important legumes, unlike the other crops in the rotation, are not appreciably retarded in their uptake of phosphorus from rock phosphate by the presence of limestone. This means that if rock phosphate is applied just ahead of clover or alfalfa—for example, at the time when the wheat or other nurse crop is seeded—the benefit of the rock phosphate is obtained immediately on the legume even tho limestone also has just been applied. Maximum wheat yields may not be obtained under these circumstances unless either the soil contains ample amounts of available forms of phosphorus or an application of superphosphate is drilled with the wheat.

In the second place, the unfavorable effect of limestone on the availability of rock phosphate to the immediate nurse crop—wheat in the above instance—is temporary. It is pronounced only so long as the alkaline areas caused by the limestone particles persist. As soon as the calcium of the limestone becomes a part of the soil clay, the unfavorable effect is markedly reduced or disappears. If the soil remains alkaline after liming, as is the case with overlimed soils or soils that are naturally alkaline, the interference with rock-phosphate availability continues. Fortunately there is practically no land in Illinois that was formerly acid and has been limed which is alkaline or even neutral. The soil, after going thru somewhat of a chemical convulsion following liming, settles down to a stable condition just on the acid side of neutral and starts the very slow process of becoming acid again, a process that requires several years. This condition of near neutrality on the acid side is ideal for the common farm crops, including the acid-sensitive legumes, as well as the grains and grasses. Such soils are commonly considered "sweet" soils so far as the need for liming is concerned and are so indicated by the chemical soil test for acidity.

In the third place, and most important of all, the success of a soil-management system that depends on rock phosphate depends also upon rotations which make use of the acid-sensitive legumes—legumes that demand liming on most Illinois soils. It is these legumes that are chiefly responsible for making the phosphorus of rock phosphate usable by other crops. There is no question that on the acid soils of Illinois the advantages of using limestone, even when applied along with rock phosphate, have exceeded any setbacks in small-grain increases. The reason is that the liming made possible the growth of soil-building legumes that would otherwise have failed.

SUMMARY AND RECOMMENDATIONS

Phosphate deficiency for crop production is widespread in the soils of Illinois. In a general way the deficiency varies in degree according to large fairly well-defined regions; but local variations also occur from farm to farm and from field to field and, in some cases, even in the same soil from year to year. Altho most soils contain enough *total* phosphorus in the depths accessible to plant roots to support probable crop yields for one or more centuries, not enough of this phosphorus exists in forms that are available to plants to meet their needs at certain critical periods in their growth.

The phosphorus-supplying power of the soil depends primarily on its content of four principal forms of soil phosphorus. These forms of phosphorus are: (1) water-soluble phosphorus, found in fresh and in actively decaying plant residues, and which, tho confined in these materials, is quickly available on root contact but escapes into the soil and becomes a part of the more permanent stock of soil phosphorus as decay advances; (2) organic phosphorus, contained in the more permanent soil organic matter and gradually released as soluble inorganic phosphate when the organic matter decomposes; (3) native phosphatic soil minerals, both primary and secondary, that are resistant to weathering and hence constitute a source with a low degree of availability for plants; (4) adsorbed phosphate, which is attached to the surfaces of colloidal clay particles and which, when newly formed, is readily available to roots that contact it.

In judging the adequacy of the phosphorus content of a soil, it is necessary to consider not only the total phosphorus requirements of the crops to be grown, but also, and more particularly, whether the concentration of the phosphorus *in the tissues of the plants* at certain stages is adequate, so the crops will grow normally and produce large yields. Two critical periods, as related to phosphorus needs, occur in the grain crops. The first is during the early life of the plant when the root system is very small; the other is at the onset of reproduction, or the bloom stage.

Certain legume crops, notably sweet clover, red clover, and alfalfa, are especially effective in obtaining phosphorus from rock phosphate, a mineral of very limited solubility, and converting it to usable form. When used in a rotation system, these legumes increase the value of rock phosphate for the other crops in the rotation.

Finally limestone, which is commonly applied to the same fields as rock phosphate, has an important influence on the availability or nonavailability of phosphorus in the soil and on its ultimate use by crops.

On the basis of the investigations reported in this bulletin, the following recommendations are made for the use of the two most important forms of phosphate fertilizer—rock phosphate and superphosphate.

Rock Phosphate

1. When used with legumes in suitable cropping systems and accompanied by liming where the soil is acid, rock phosphate is an effective and economical material for building up the productive level of many phosphorus-deficient soils.

2. Rock phosphate is especially desirable as a direct fertilizer for many legumes. When legumes thus fertilized are used as green-manure crops, or when a second growth can be plowed down before grain is planted, the grain crop will profit from the action of the legumes in converting the phosphorus of the rock phosphate to forms more readily available for plant use.

3. Altho the grains and grasses are also able to make direct use of phosphorus supplied to the soil by rock phosphate, they utilize it at a much slower rate than do the legumes. If it were the sole source of phosphorus for these crops, they would not be able to get their necessary supply fast enough to make it possible for them to produce maximum yields. Combined with phosphorus from the soil, however, the supply from rock phosphate is adequate for maximum yields on some soils. On other soils the deficiency is not made up by rock phosphate and increases in yield follow the application of superphosphate, especially in the case of wheat.

4. The best time to apply rock phosphate is usually before or at the time of seeding the crops it will benefit most—alfalfa, sweet clover, red clover, and other legumes. On plowed land the rock phosphate is generally broadcast and mixed with the surface soil while the seedbed is being prepared.

5. Limestone will interfere less with the response of wheat to rock phosphate if the rock phosphate and limestone are not applied at the same time. The interference, however, is temporary, lasting only as long as free calcium carbonate remains in the soil; and it is of small significance compared with the value of the limestone in promoting the growth of legumes.

Superphosphate

1. Used along with limestone and legumes, superphosphate has a place in Illinois soil-improvement programs. When so used, more of it is needed than is required for the direct fertilization of individual

crops such as wheat and corn; and it is important that fully adequate amounts be supplied.

2. Superphosphate can also be profitably used for direct fertilization of many crops, especially the grain crops such as wheat and corn. With wheat it is useful under a wide range of soil conditions, causing worth-while increases in yields not only on comparatively poor soils but also on soils which, while fairly fertile, do not contain enough available phosphorus to meet the extra demands at the critical periods of plant development. In the case of corn, especially the high-yielding hybrids growing on fertile soils, the addition of a phosphate-potash fertilizer near the hill at planting time is frequently necessary in order to bring about maximum yields. Used in this way, superphosphate may be considered a last step in soil improvement; that is, a means of increasing production on an already fertile soil.

3. When superphosphate is used at seeding time, it is usually most effective if applied in a band near the seeds. So placed, the root systems of the young plants can tap it effectively while they are still too small to contact a large volume of soil. Concentrating the superphosphate in a small area has another advantage: the soil immediately surrounding it becomes saturated, thus reducing the conversion of the superphosphate into less soluble forms before the plants have a chance to take it up and use it.

Two Forms Are a Team

The investigations reported in this bulletin furnish evidence that both rock phosphate and superphosphate can play important roles in meeting the phosphorus requirements of Illinois soils for the production of maximum yields of the important farm crops.

Not only the two phosphates themselves but also the soils of Illinois differ greatly in physical, chemical, and other properties, and these differences necessitate the application of the two forms in a different manner and their use in different situations. On some soils rock phosphate is the more economical source of phosphorus for building up the productive capacity. On other soils and especially with certain crops, rock phosphate does not adequately reinforce the soil supply and superphosphate is necessary in order to produce optimum crop yields. In a great many cases either rock or superphosphate is an effective and economical means of meeting the phosphorus requirements of crops and the choice between them is merely a matter of preference.

These two kinds of phosphate may then be considered a team, both members of which help to pull the load. If each is used in the places and in the manner suited to its greatest effectiveness the results will be an advantage to the user and an aid in the conservation of soil fertility.

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How much phosphorus do farm crops need?

Will the amount vary during the season? Under what conditions will the soil supply adequate phosphorus, and when is it necessary to add fertilizers?

Early investigations designed to answer these questions were based on chemical analysis of the crops at harvest. Such analyses showed how much phosphorus the crops had actually absorbed but not how much they would have absorbed had the soil supplied it, nor whether adequate amounts had been taken up at all stages of growth.

The viewpoint developed in this bulletin goes beyond a measure of actual phosphorus absorption by crops to consider how much phosphorus must be present in the plant tissues at different stages of growth if there is to be no stunting and no limitation in yield.

The study is a progress report of investigations carried on during the past several years at the Illinois Station. It makes no attempt to set down hard-and-fast rules about the application of phosphate fertilizers. Rather it explains what at present seem to be the fundamental principles on which all sound practices in the use of these fertilizers must rest.

15,050—4-42—23035-S